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Comparison of 4- and 5-beam acoustic Doppler current profiler configurations for measurement of turbulent kinetic energy at a potential marine renewable site

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Abstract

Acoustic Doppler current profilers (ADCPs) are commonly used to assess mean currents and turbulence at energetic sites. Since 2014, five-beam ADCP configurations have become more common, but conventional analysis of turbulence properties is still based on the four-beam Janus configuration. We use measurements from a single site to investigate whether improved estimates of turbulent kinetic energy (TKE)are made possible by the addition of a fifth vertical beam. We conclude that four-beam estimates of TKE are suitable in most cases, and exhibit lower variance than five-beam estimates, but are more prone to contamination by wave activity.

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Keywords: ADCP; Turbulence; Tidal energy; Ocean current

Nomenclature

B_m'	fluctuation velocity along the direction of the *m*th ADCP beam
H_S	significant wave height
k; k_4, k_5	turbulent kinetic energy density; estimates of k obtained with four- and five-beam ADCP configurations
u_i'	component of fluctuation velocity along the *i*th spatial dimension

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θ	angle of inclination for off-vertical ADCP beams
ξ	proportion of turbulent kinetic energy contained in vertical fluctuations

1. Introduction

Tidal energy converters (TECs) are renewable energy devices that transfer the kinetic energy of tidal currents into electricity, with most designs using similar principles to conventional horizontal-axis wind turbines. However, the marine environment in which they are deployed and operated poses its own set of technical hurdles that must be addressed (1) (2) (3). Tidal current turbulence, defined as the fine-scale fluctuations in mean flow manifesting as discrete eddies and vortices caused by topographic, bathymetric and frictional effects, is one of these challenges, and an important consideration for the development of TECs due to its impact on loading, reliability and fatigue (4) (5). Ocean turbulence differs from atmospheric turbulence as the ocean's surface acts as an upper-bound, where surface waves propagate, which can increase turbulence by introducing additional mass and momentum to the flow (6). Therefore, knowledge of turbulence at tidal energy sites is of crucial importance for the design of resilient and efficient TECs.

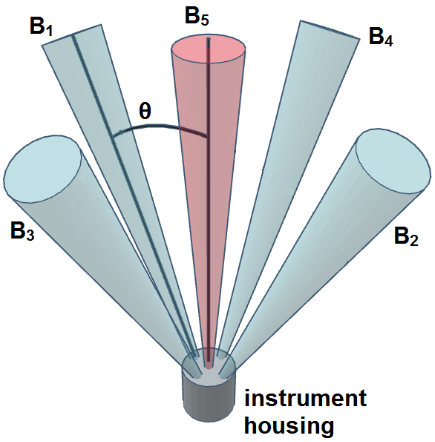

Fig. 1: Simplified diagram of upward-looking five-beam ADCP showing beam layout. Blue beams are also present in conventional four-beam 'Janus' configuration.

Acoustic Doppler current profilers (ADCPs) are one of the most widely-used tools for measuring properties of marine flows, including turbulence characteristics. ADCPs use the Doppler shift in the echoes of pings along directed acoustic beams to measure flow velocities (7). The specifics of an ADCP model and its deployment will vary according to the needs of a particular measurement campaign; however, for highly energetic sites suitable for TECs the standard is to use an upward-looking ADCP with three or four diverging beams (8) (9) (10). Five-beam ADCPs are similar to the conventional four-beam 'Janus' configuration (cf. figure 1), but with the addition of a vertical beam. Such devices have seen occasional use for approximately a decade (11), but have only recently become widely available as off-the-shelf instruments. In this paper, we examine how measurements of turbulence parameters may be improved by the additional data available from a fifth ADCP beam.

Each ADCP beam samples a single component of velocity from separate locations, so it is not possible to get direct measurements of the full turbulence velocity field at any given point. However, under certain assumptions regarding the flow statistics across the sampled area, it is possible to calculate some parameters of the turbulence.

1.1. Instrumentation deployment

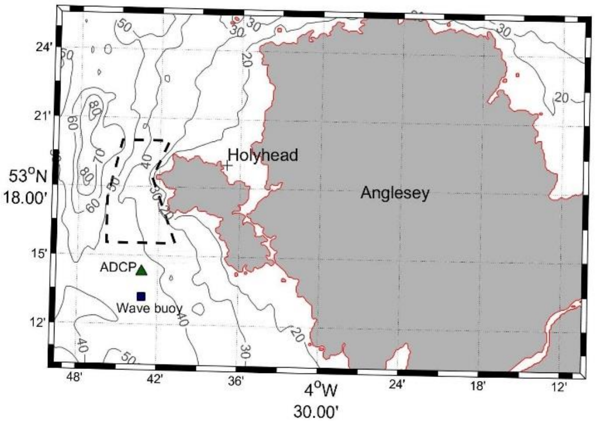

Fig. 2: Location of ADCP and wave buoy off the coast of Anglesey. Extent of West Anglesey Demonstration Zone (WADZ) shown by dashed black line. Image credit: Simon Neill

All data presented in this paper is taken from a deployment of an RDI Sentinel V five-beam acoustic Doppler current profiler (ADCP) near the West Anglesey Demonstration Zone (WADZ) off the Welsh coast (UK) between 19/9/14 and 19/11/14; a map of the deployment zone is shown in figure 2. Concurrently with this deployment, a directional wave buoy measured significant wave height and period approximately 2 km to the south of the ADCP location. Water depth at the ADCP's location varied between 41.1 m and 46.2 m through the deployment period, and peak spring currents were 2.48 ms^{-1}. There was a blanking distance of 1.89 m between the instrument and the first bin, and subsequent bins had a vertical separation of 0.6 m. The ADCP collected fifteen minutes of data every hour; during a burst, the sampling rate was 2 Hz. The ping frequency was 491 kHz, measurements having a standard deviation, $\sigma = 0.28$ cm s^{-1}. Further details of the site can be found in references (12) and (13).

1.2. Measuring turbulence with ADCPs

In the current work, we characterize turbulence through examination of the turbulent kinetic energy (TKE) density, k, which expresses the amount of energy contained in turbulent velocity fluctuations per kilogram of fluid. Using index summation, we can relate k to the velocity fluctuations as:

$$k = \tfrac{1}{2}\langle u_i' u_i' \rangle, \tag{1}$$

where u_i' denotes the velocity fluctuation in the ith spatial dimension, and angle brackets denote an ensemble average – in practice, this is approximated by an average over a single fifteen-minute burst. k is extremely useful for characterising turbulence – in its most basic sense, it can be thought of as a measure of how much turbulence there is – and so it is a good parameter for assessing how measurement of turbulence is changed by the use of five-beam rather than four-beam ADCP configurations.

As mentioned in the introduction, in order to analyse turbulence with ADCP measurements it is necessary to make some assumptions regarding the behavior of the flow statistics across the volume of space in which the ADCP measures. Specifically, we must assume that the second-order statistics are homogeneous across all beams, and we must assume that they do not significantly change over the averaging period (in this case, over each fifteen minute burst). In a conventional four-beam configuration, it is also necessary to assume that the anisotropy of the components of turbulence can be parametrized by a single variable ξ, representing the proportion of TKE contained in vertical fluctuations (14) (15). This is typically assigned the value $\xi = 0.1684$, following the work of Nezu & Nakagawa (16).

Using these assumptions, it is straightforward to relate the variance in the measured along-beam velocities to k. A detailed derivation can be found in the previous references; in this paper we simply present the formulations relating the beam variances to k using the four- and five-beam configurations, which are distinguished as k_4 and k_5.

$$k_4 = \frac{\sum_{m=1}^{4} \langle B_m'^2 \rangle}{4 \sin^2\theta \left(1 - \xi\left(1 - \cot^2\theta\right)\right)} \tag{2}$$

$$k_4 = \frac{\sum_{m=1}^{4} \langle B_m'^2 \rangle}{4 \sin^2 \theta} + \left(\frac{1}{2} - \cot^2 \theta\right) \langle B_5'^2 \rangle \tag{3}$$

In equations (2) and (3), B_m' denotes the fluctuation velocity along the *m*th beam, and θ denotes the inclination angle of the off-vertical beams (cf. figure 1); for the ADCP used in the current study, θ = 25°. Such use of beam variances to calculate k and other turbulence parameters is conventionally referred to as the variance method.

1.3. Bias and variance in k

The above expressions relating k and beam variances are simplified in that they do not consider the effect of instrument noise (17). To understand how noise affects the estimates of TKE density, we assume that the effect of noise on a given beam can be represented as a zero-mean Gaussian random variable error that causes a difference between the along-beam velocity values as measured and the actual velocities in the flow-field (15). We also assume that this noise is a property of the instrument alone, and is thus uncorrelated with the real velocity fluctuations (18). With these assumptions, it follows that the estimated variance for the along-beam velocity of the *m*th beam, $\langle B_m'^2 \rangle$, will be positively biased by an amount equal to the variance of the Gaussian noise term. Following this reasoning, we presume that for a sufficiently large number of beam variance estimates, particularly if some are taken at slack water, there will be at least some estimates for which the true along-beam velocity variance is negligibly small in comparison to the noise variance. We thus estimate the noise-induced bias in the beam variance as equal to the smallest observed value of the beam variance itself (recall that each observation is a fifteen minute burst average). It is then a trivial exercise to derive the bias in the TKE estimates from the biases of the individual beam variances. All results presented in this paper have been corrected for bias using this method.

Determining the variance of TKE estimates is not quite so straightforward. We start by observing that equations (2) and (3) are both of the form $k = \sum_m c_m \langle B_m'^2 \rangle$, where the variables c_m are constant coefficients. It is then clear that in calculating the variance of k, we are finding the variance of a sum of weighted random variables:

$$\mathrm{Var}(k) = \sum_m c_m^2 \, \mathrm{Var}(\langle B_m'^2 \rangle), \tag{4}$$

Thus, in order to find the variance of k, we must first evaluate $\mathrm{Var}(\langle B_m'^2 \rangle)$. Since each variance estimate is calculated by an ensemble average over the entirety of a fifteen-minute burst, we do not have a broader population of $\langle B_m'^2 \rangle$ values that can be used to calculate $\mathrm{Var}(\langle B_m'^2 \rangle)$; we therefore use bootstrapping from each burst's population of $B_m'^2$ values to estimate the variances of variances.

2. Results

An overview comparison of the four- and five-beam estimates of turbulent kinetic energy for the entire deployment period is presented in figure 3. This figure also shows the significant wave height (H_S) as measured by the wave buoy during the same period.

Note the colour range used for these contour plots does not cover the full range of estimated k values, which go as high as 1.10 m^2s^{-2} in the four-beam case and 1.18 m^2s^{-2} in the five-beam case. However, as is obvious from the plots, these extremely high values are always found near the surface and coincide with strong wave activity. We conclude, then, that these extreme observations are a result of the variance method including the oscillation about mean velocity due to wave orbital motion, rather than random velocity fluctuations due to turbulence.

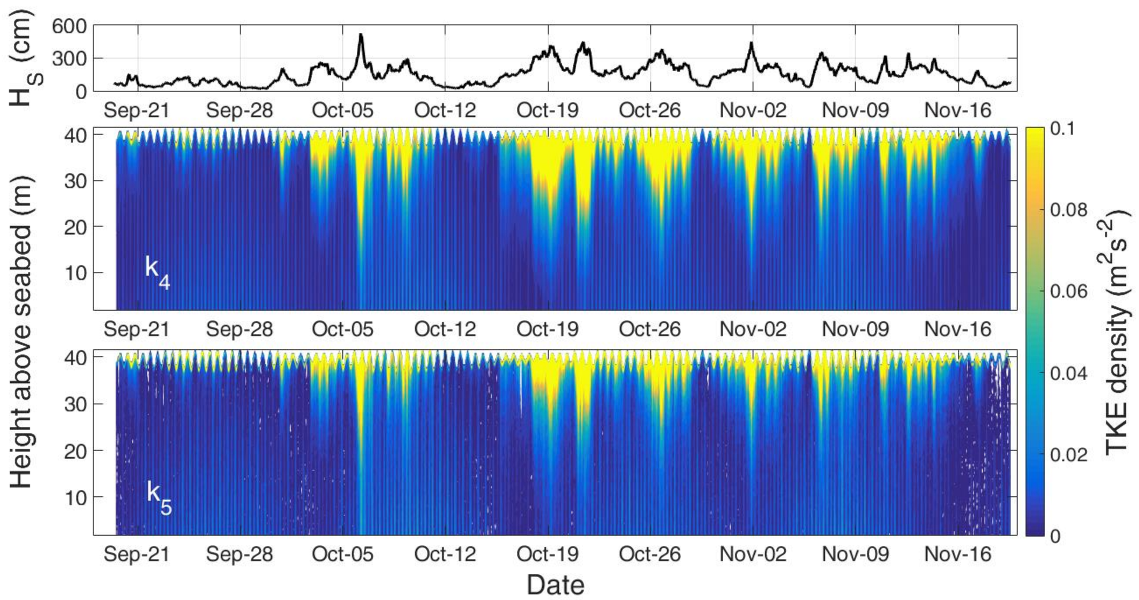

Fig. 3: Upper panel shows significant wave height from wave buoy deployment. Middle panel shows k_4 and lower panel shows k_5. Data appearing in white in lower panel corresponds to k_5 values that are below zero after bias correction; see text for discussion.

The formulation of the relationship between k_4 and the beam variances $\langle B_m'^2 \rangle$ is such that k_4 is expressed as a sum of squares (cf. equation (2)), and will therefore always be positive even after correction for the positive bias introduced by Doppler noise described in section 1.3. In contrast, for all practical values of θ we have $\cot^2 \theta > \frac{1}{2}$, meaning that equation (3) for k_5 includes a difference of squares, and therefore may take a negative value. The true value of k must always be greater than zero, so any values of $k_5 < 0$ shown as white in the lower panel of figure 3 must be caused by variance in the estimate. Based on the variance associated with measurement error as calculated with equation (4), only 0.37% of k_5 observations fall more than one standard deviation below zero, and only 0.12% more than two standard deviations below. This is well within what is expected for a normally-distributed observation error.

Overall, k_4 and k_5 estimates of TKE density are very similar, suggesting that any improvement introduced by using a five-beam configuration will be relatively minor. It is difficult to compare k_4 and k_5 across the whole water column due to the strong dominance of wave effects in the near-surface region. We attempt to mitigate this by comparing only the deepest 20 m of the column, but even with this restriction wave action still has a significant effect on estimates of k. To further reduce the influence of wave effects, we exclude bursts from times where H_S is above its own 75th percentile. With this exclusion condition in place, k_4 and k_5 estimates of TKE density differ by only 3.6% on average, and by no more than 10.7% at any particular bin height.

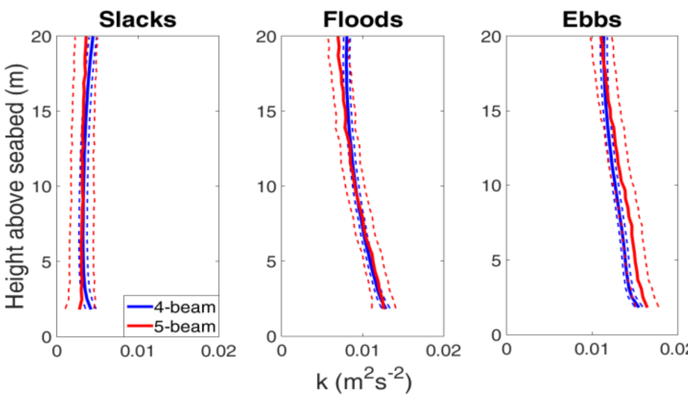

Fig. 4: Mean k_4 and k_5 profiles for the lower 20 m of the water column, separated by tidal phase. Dashed lines show one standard deviation above and below mean value. Times of strong wave activity have been excluded as described in text.

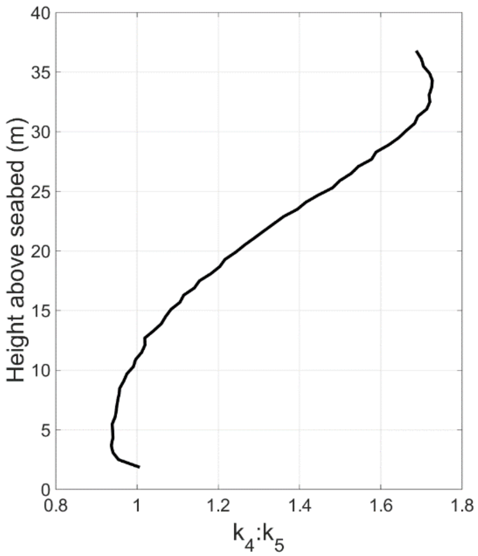

Fig. 5: Ratio of four- and five-beam estimates of TKE density for whole water column

The similarity of k profiles between the two formulations persists if we examine slack, flood and ebb phases separately, as depicted in figure 4. The two formulations differ by an average of only 4.2% on floods and 5.8% on ebbs; the slack average error takes a higher value of 9.9%, but this is due to the low turbulence at slack meaning that a similar difference in the absolute values of k_4 and k_5 yields a larger relative difference. Note that there is a tidal asymmetry (19) in k at this location: TKE density is between 26% and 32% lower on floods than on ebbs, depending on which estimate is used.

The standard deviations of the k profiles shown in figure 4 also illustrate the fact that variance in the estimate of TKE density is significantly greater in the five-beam case. On average, Var(k_5) exceeds Var(k_4) by a factor of 8. This is due to the fact that each of the beam variances is heavily weighted (in the sense of equation 4) compared to the four-beam case; there is a particularly heavy weighting on the variance of the vertical beam. The increased variance of the k_5 estimate is a consequence of this weighting in combination with the fact that the vertical beam is narrower, and hence noisier.

As mentioned above, the TKE density estimates in the upper half of the water column are biased high by wave action, and thus cannot be taken as an accurate measure of the actual energy contained in turbulent fluctuations. It is nonetheless instructive to compare the four- and five-beam estimates for the whole water depth, as shown in figure 5. These results show that the k_4 estimate of TKE density tends to exceed the k_5 estimate by an increasing margin as we move upwards through the water column. This implies that four-beam observations of k are more contaminated by wave action than the five-beam case. Indeed, near-surface k_4 is on average greater than k_5 by a factor of 1.9, although only slightly better correlated with H_S (R = 0.88 vs. R = 0.84).

3. Conclusions

The overview comparison of four- and five-beam estimates of TKE density shown in figure 3 indicates that using the data from the vertical beam to calculate turbulence strength will not lead to any great changes in observations of k. This is further borne out by the more detailed breakdown of TKE estimates into tidal phases shown in figure 4, which indicates that, except where wave action starts to dominate turbulent fluctuations, k_4 and k_5 agree to within one standard deviation. This leads to another salient point: due to the heavier weighting of the scalar coefficients relating beam variances to the TKE density in the five-beam case, the variance of k_5 is much greater than the variance of k_4. Therefore, observations from this study indicate that using data from the additional 5th vertical beam in an ADCP does not substantially improve the ability to estimate TKE density in low wave climate regions, and users may prefer to vertical beam data for measurement of other parameters e.g., surface tracking.

We also find, however, that since the variance method cannot distinguish between velocity fluctuations driven by turbulent action and those driven by wave action, strong waves lead to unrealistically high estimates of TKE density. As shown in figure 5, this effect is more pronounced for four-beam estimates. Thus, for sites where significant wave activity is expected and where measurements of turbulence near the surface are of interest, a five-beam configuration may be preferred.

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